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Road organo-mineral mixtures based on oil sludge

O.N. Ilina*, I.B. Ilin,
Kazan State University of Architecture and Engineering, Kazan, Russia,
** E–mail: ilinaon@inbox.ru*

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Abstract. Nowadays the development and implementation of modern construction technologies using oil wastes is gaining importance in road construction. Most of these wastes are stored in lagoons, which occupy vast territories, pollute the atmosphere, groundwater, soil and harm the environment. The purpose of the study is the development of organo-mineral mixtures composition based on oil sludge and technology for road construction with their application. The experimental research methods include the determination of strength, water resistance, water saturation, and swelling indicators of materials of various compositions. We also established optimal limits for factors variation that ensure the required reliability of the results. As a result of experimental studies we established that the optimal content of solid oil sludge in the composition of the developed materials is 30%, crushed stone –70% and the content of Portland cement is 6%. Physical and mechanical properties of the organic-mineral mixture based on oil sludge comply with regulatory requirements. During experimental and industrial implementation of the research results on4 experimental road sections we developed road pavement base construction technology of organo-mineral mixture based on oil sludge. It is performed by commercially available road-building machines with leading mechanisms recycler using the method called "mixing on the road". We developed the operation schedule of oil sludge preliminary preparation at the special plant. Prepared oil sludge is a secondary raw product for road construction materials that is uniform in colour, grain composition, mass fraction of water and oil. Suggested modern technology for road pavement base construction allows making the oil sludge processing cycle absolutely complete and eliminates the formation of industrial by-products. This is an integral part of natural resources rational use and saving in material resources consumption. Technology application also contributes to the environment ecological state improvement in the areas of oil production and refining.

1. Introduction

In road construction, the integrated utilization of industrial wastes is currently gaining importance, taking into account the growth of environmental problems and a decrease in the level of target natural components in the feedstock. The task of raw materials integrated use for the road construction industry is natural materials rational use and the involvement of industrial waste in the process. Industrial waste can be of many types [1–5]. They differ in grain size composition, chemical composition and degree of safety. Therefore, the main trend in measures to protect the population and the environment from industrial waste harmful effects is the development and implementation of modern technologies for road construction using industrial waste and recycled products efficient use in the regions' economy [6-10].Oil sludge represents waste from the oil industry which is formed during the operation of oil fields due to discharges during oil treatment, tank cleaning, drilling activity, and discharges during testing and workover.

The annual oil production in Russia continues to grow steadily from 488 million tons in 2008 to 555.7 million tons in 2018, while oil refining depth is about 80%. The bulk of oil in Russia is now produced in three:

- Khanty-Mansijsk Autonomous District, the Krasnoyarsk Region (West-Siberian Basin) – up to 70% of All-Russia oil production;

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- Tatarstan, Bashkortostan, the Orenburg Region (Volga-Ural Basin) – up to 20% of All-Russia oil production;
- Khanty-Mansijsk Autonomous District, the Komi Republic (Timan-Pechora Basin) –up to 10%of All-Russia oil production.

The annual volume of oil sludge formation in the Russian Federation varies depending on the source from10 to 25 million tons while the volume of use and disposal of this waste is not more than 10%. In the Republic of Tatarstan where the oil industry is highly developed, oil production in 2018 reached 35 million tons, the volume of oil sludge is also increasing annually about 200 thousand tons and taking into consideration the accumulated volumes, there are reserves of oil sludge for the possibility of building 500 km of roads. Most of this waste is stored in lagoons, which occupy vast territories, polluting the atmosphere, groundwater, soil, and causing enormous damage to the environment. Nowadays the most common methods for the disposal of oil sludge can be classified into mechanical, physical and chemical, thermal, biochemical and combined methods [11-16]. The common disadvantage of the disposal methods and technologies for oil sludge processing is their poor efficiency and high material, energy and financial costs for their implementation; the disposal cycle is also incomplete and produces secondary waste. The introduction of a particular processing technology depends on the composition of the raw materials used, the nature of the oil sludge, the ratio of organic and inorganic components in them, environmental requirements, as well as the technical capabilities of the plant. All these factors make it difficult to process oil sludge fully and intensively with extreme environmental safety and non-waste technology.

Oil sludge has a wide range of composition and physical and mechanical characteristics. Resins, paraffins and other high molecular weight compounds that are parts of oil sludge have surface-active and binding properties. It is this feature of oil sludge that can be effectively used in road construction, which is confirmed by previous studies [17–22]. The Republic of Tatarstan has significant reserves of weak mineral materials which can be effectively used in road construction after special treatment with binders. Based on economic and environmental prerequisites some part of the material while processing may be presented by oil sludge. The purpose of the study is the development of organo-mineral mixtures compositions based on oil sludge and the technology of pavement base construction applying them. To achieve it, the following tasks are defined: research and optimization of the composition of organo-mineral mixtures based on oil sludge; development of technology for pavement base construction with oil sludge preliminary preparation; experimental and production implementation of the research results.

2. Methods

Experimental studies of organic-mineral mixtures based on oil sludge were carried out in accordance with the International standard of Commonwealth of Independent States GOST 30491 "Organic-mineral mixtures and soils, reinforced with organic and complex binders, for road and airfield construction" [23]. At the stage of exploration, we investigated and optimized the compositions of the developed materials based on oil sludge, and established the optimal limits for factors variation, we also developed and mastered methodology to ensure the required reliability of the results. When the content of oil sludge is more than 50 %, even with a sharp increase in the required amount of expensive imported binder, Portland cement, characteristic value of the material is not always achieved, and when the content of oil sludge is less than 30 %, the volume of disposal of this waste is reduced, which is not feasible both economically and technically. Thus at the research main phase the composition of the developed material includes crushed limestone 50–70 % and solid oil sludge in the amount of 30–50 %, as a binder we used Portland cement up to 12 %, water up to 8 %.

Manufacturing, storage and testing of samples of organo-mineral mixtures based on oil sludge was carried out in accordance with the International standard of Commonwealth of Independent States GOST 12801 [24]. Samples were created in the following sequence: first, we mixed crushed stone and oil sludge until a homogeneous mixture was obtained. Next, we added cement and water which were then mixed. Then we placed the obtained mixture into cylinder molds with the diameter and height of 71.4 mm. Dimensions of cylinder molds are selected taking into account the maximum size of the aggregate. Metal cylinder molds were preluded with mineral oil. Compaction of samples from the mixture was carried out on hydraulic press MS-500 under a pressure of 40.0 ± 0.5 MPa for 3.0 ± 1.0 min. During compaction, a two-sided load application was ensured, which we achieved by transferring pressure to the compacted mixture through two liners moving freely towards each other in the mold. The samples from mixtures were stored at the temperature of 20 °C ± 5 °C in a tub with a hydraulically sealed desiccator. Tests for water-saturated samples from mixtures were carried out for 48 hours. During the first 6 hours samples were immersed into water at 1/3 of the height, the remaining 42 hours – at full height. Density is found according to theInternational standard of Commonwealth of Independent States GOST 12801 [24].

The determination of the compressive strength includes determining the load required for sample failure under given conditions. The samples compressive strength is determined using the press at the press plate rate of motion (3.0 ± 0.3) mm/min. The sample is placed in the center of the press bottom plate, then we lower the top plate and stop it 1.5–2 mm above the surface level of the sample. We can achieve the same result by a corresponding rise of the press bottom plate. After that, we turn on the electric motor of the press and start loading the sample. The maximum dynamometer indicated value is taken as the ultimate breaking load.

Compressive strength R_{STR}, MPa, is calculated according to the formula [24]:

$$R_{STR} = \frac{P}{F} 10^{-2}, \quad (1)$$

P is ultimate breaking load, N;

F is original cross-sectional area of the sample, cm^2;

10^{-2} is conversion factor in MPa.

The arithmetic mean of the tests of three samples is taken as the result of the determination. Determination of water saturation represents the determination of the amount of water absorbed by the sample at a given saturation mode. Samples from mixtures, weighed in air and in water, are placed into a vessel with water at the temperature of (20 ± 2) °C. The water level above the samples should be at least 3 cm. Full water saturation of samples with a height and diameter of 70 mm is carried out for 3 days, while in all cases, on the first day, the samples are immersed into water at 1/3 of the height, and on the subsequent days – completely. To prevent drying of the samples immersed in water at 1/3 of the height, saturation is carried out in a hydraulically sealed tub. After that, the samples are removed from the vessel, weighed in water, and then wiped with a soft cloth or filter paper and weighed in air.

Water saturation of the sample W, %, is calculated according to the formula [24]:

$$W = \frac{m_5 - m}{m_2 - m_1} 100, \quad (2)$$

m is mass of the sample weighed in the air, g;

m_1 is mass of the sample weighed in water, g;

m_2 is mass of the sample, kept in water during 30 min and weighed in air, g;

m_5 is mass of water saturated sample weighed in air, g.

Arithmetic mean of three values rounded to the first decimal place is considered as the result of water saturation determination.

Swelling is defined as sample volumetric gain after its saturation with water. To determine the swelling we use the data obtained in determining the average density and water saturation.

Swelling of the sample H, % by volume, is calculated according to the formula [24]:

$$S = \frac{(m_5 - m_6) - (m_2 - m_1)}{m_2 - m_1} 100, \quad (3)$$

m_6 is mass of water saturated sample weighed in water, g.

The arithmetic mean of three defined values rounded to the first decimal place is taken as the result of swelling determination.

The value of water resistance coefficient includes the assessment of the decrease in compressive strength of the samples after exposure to water under vacuum. Samples from mixtures, weighed in air and in water, are placed in a vessel with water at the temperature of (20 ± 2) °C. The water level above the samples should be at least 3 cm. The vessel with the samples is placed in a vacuum plant, where the pressure of not more than 2000 Pa (15 mm Hg) is created and maintained for 1 h. Then the pressure is brought to atmospheric pressure and the samples are kept in the same vessel with water at the temperature of (20 ± 2) °C for 30 minutes. After that, the samples are removed from the vessel, weighed in water, wiped with a soft cloth and weighed in air.

Water resistance is calculated with the accuracy up to the second decimal place by the formula [24]:

$$K_B = \frac{R_{STR}{}^W}{R_{STR}{}^{20}}, \quad (4)$$

$R_{STR}{}^W$ is compression resistance of water saturated samples at the temperature (20±2) °C, MPa;

R_{STR}^{20} is compression resistance of samples before water saturation at the temperature (20±2) °C, MPa.

The studies were conducted using the local crashed stone M400, obtained in the quarry of the Republic of Tatarstan. Table 1 shows the physical and mechanical properties of the crushed stone; Table 2 represents the grain composition of the crushed stone.

Table 1. Physical and mechanical properties of the crushed stone mixture.

Fraction size, mm	Packed density, kg/m^3	Water absorption , %	Wear value grade	Strength grade	Frost resistance grade index	Optimum moisture content%
0–20	1700	7.9	I3	400	10	6

Table 2. Grain composition of the crushed stone mixture.

Grains maximum size, mm	Total sieve residue percentage with the size of the mesh, mm						
	10	5	2.5	1.25	0.63	0.315	0.14
20	5	25	35	50	60	75	85

Oil sludge for laboratory research was selected from the lagoons and has the composition presented in Table 3. The content of the most active components of the oil sludge i.e. asphaltenes and resins is 5.5–11 %.

Table 3. Composition of the oil sludge.

Content, % mass					
Asphaltenes	Resins	Paraffines	Unsaturated hydrocarbons	Water	Mechanical admixtures
1.5–4.0	4.0–7.0	10.0–50.0	6.0–10.0	2.0–10.0	40.0–60.0

For mixture processing we used Portland cement CEM II 42.5N DO which is highly recommended for road construction [25]. Process water meets the requirements of the standard [26].

3. Results and Discussions

The results of experimental studies of organo-mineral mixtures based on oil sludge showed the compliance of their indices with the standard values. The main results of organo-mineral mixtures indices are given in Table 4, Figures 1–4. Analysis of the data obtained shows that the optimal content of solid oil sludge in the composition of the developed materials is 30 %, crushed stone is 70 % and the content of Portland cement is 6%. Adding of a binder (Portland cement) into the organo-mineral mixture provides 1.25–1.28 times increase in the material compressive strength and ensures compliance with regulatory requirements (Figure 1). Organo-mineral mixture water saturation and swelling indices decrease with 1.4 times increase in the amount of oil sludge (Figure 3).

Table4. Physical and mechanical parameters of organo-mineral mixtures.

Position	Mixtures composition, %			ρ, g/cm^3	Results of testing the mixture sample sat 28 days				
	Oil sludge	Portland cement	Crushed stone M400		R_{STR}, MPa	R_{water}, MPa	Water resistanc e coef.	W, %	H, %
1	50	6	50	1.90	1.89	1.46	0.77	4.63	0.87
2	50	8	50	1.91	2.10	1.88	0.89	5.04	0.82
3	50	10	50	1.92	2.10	1.90	0.90	4.80	0.71
4	50	12	50	1.93	2.34	1.87	0.80	3.82	0.52
5	30	6	70	1.96	2.29	1.77	0.77	5.39	0.69
6	30	8	70	1.96	2.30	1.99	0.86	5.45	0.70
7	30	10	70	1.96	2.35	1.98	0.84	5.35	0.59
8	30	12	70	1.96	2.71	2.22	0.82	5.26	0.54
9	Requirements of the International standard of Commonwealth of Independent States GOST 30491					≥1.4	≥0.6	≤10	≤2

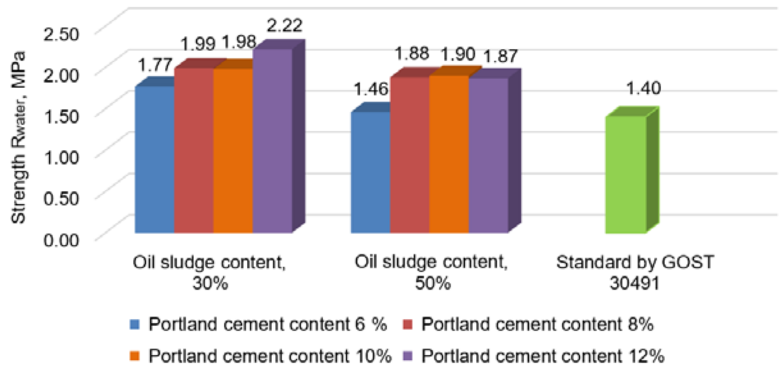

Figure 1. Compressive strength of water-saturated samples depending on the content of Portland cement and oil sludge.

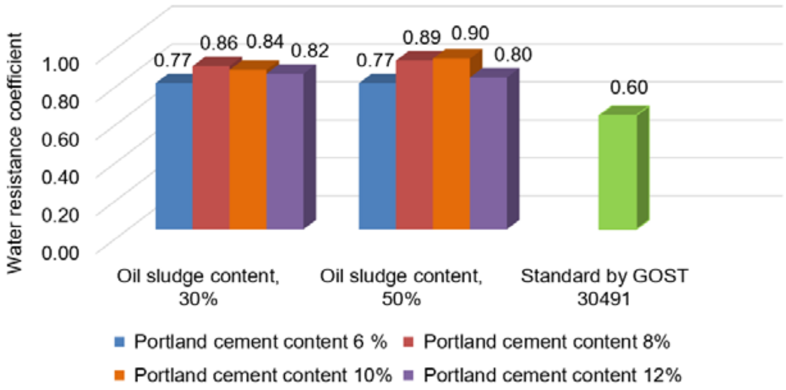

Figure 2. Samples' water resistance coefficient depending on the content of Portland cement and oil sludge.

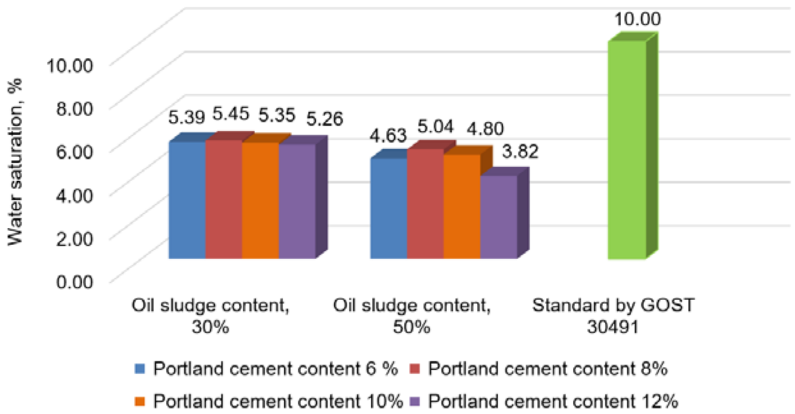

Figure 3. Samples water saturation depending on Portland cement and oil sludge content.

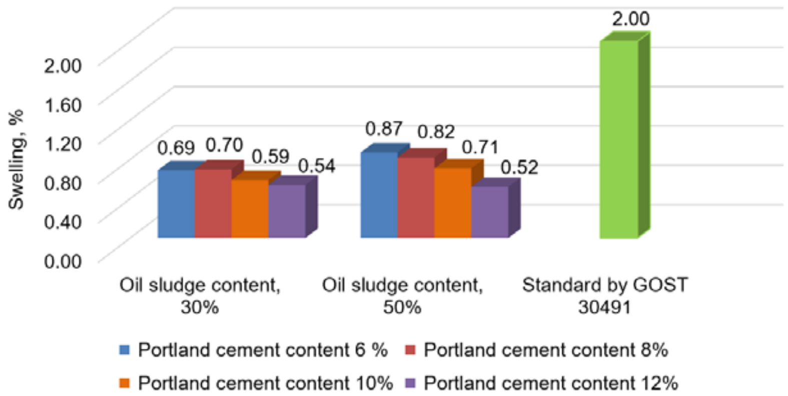

Figure 4. Samples swelling depending on Portland cement and oil sludge content.

Processing of the research results was performed using elements of the analysis of variance and regression analysis (Figure 5). The correctness of strength, water saturation and swelling indicators dependence descriptionis confirmed, after evaluating the value of the coefficients using the method of successive regression analysis, the following mathematical models are obtained which link the characteristics of the organo-mineral mixture with the content of oil sludge (X_1), crushed stone (X_2) and cement (X_3):

$$R_{STR} = - 3.09414+0.03449X_1+0.05229X_2+0.35471X_3-0.02262X_3^2$$

$$W = -1.25771+0.17802X_1+0.01477X_2+0.13038X_3$$

$$S = -2.15029+0.0462X_1+0.02656X_2+0.04168X_3-0.01582X_3^2$$

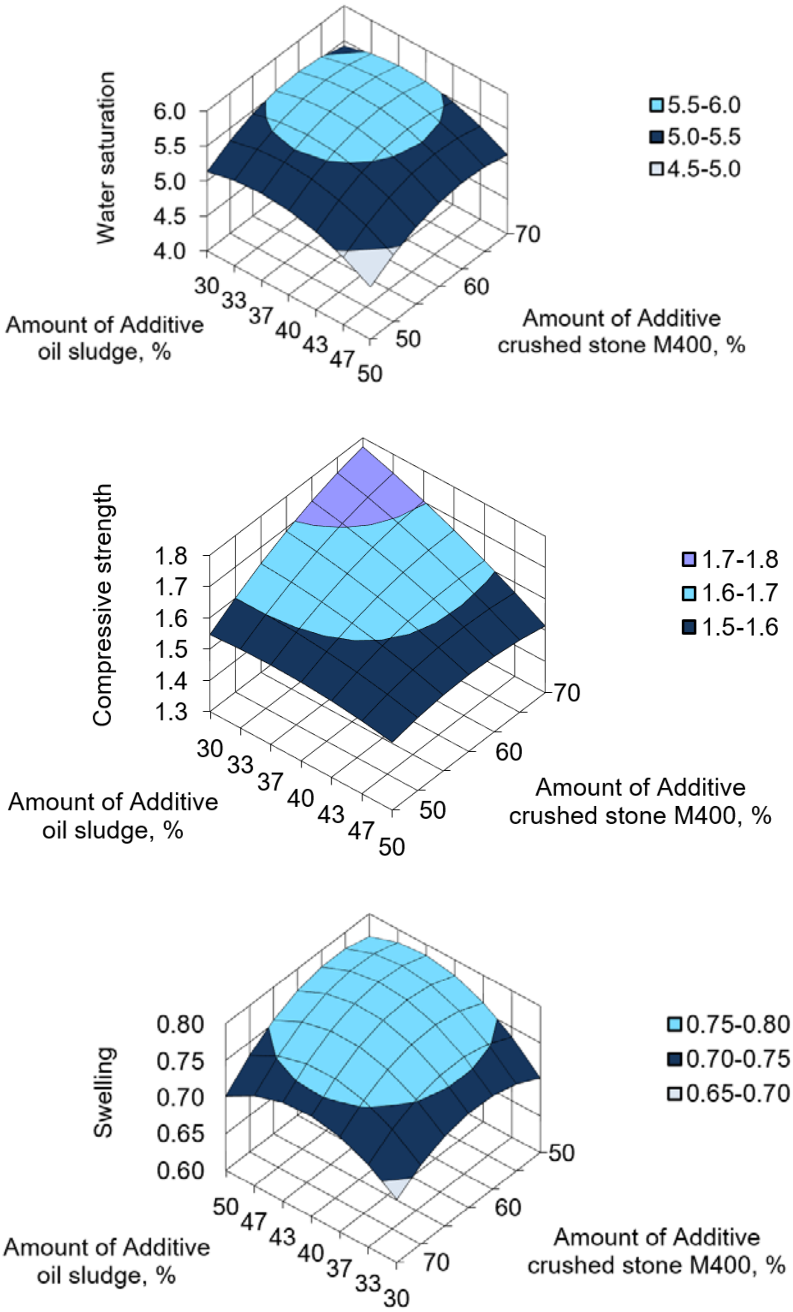

Figure 5. The influence of solid oil sludge, crushed stone and Portland cement content on the indicators of compressive strength, water saturation and swelling of the developed material.

Based on research and development of the technological parameters of organo-mineral mixtures creation and application for their intended purpose, a scheme for preliminary technological preparation of oil sludge was developed and introduced to ensure its uniformity in composition and properties. To obtain a sufficiently uniform organo-mineral mixture, the characteristics of which largely depend on the amount of oil sludge and its composition, it is necessary to achieve the uniform spreading of its components. Oil sludge with higher uniformity of composition and properties was obtained after processing it in the oil sludge plant. The operation schedule represents (Figure 6): using a loader we deliver oil sludge estimated volume from the lagoon to the preparation and storage site, then we load it into the preliminary preparation receiving hopper, then we process it in the mixer and transfer to the loader by conveyor, then oil sludge is transported by dump truck to site or stacked on the site of preparation and storage.

Prepared oil sludge is a material homogeneous in color, composition, moisture and according to physicochemical parameters must meet the requirements and norms given in Table 5.

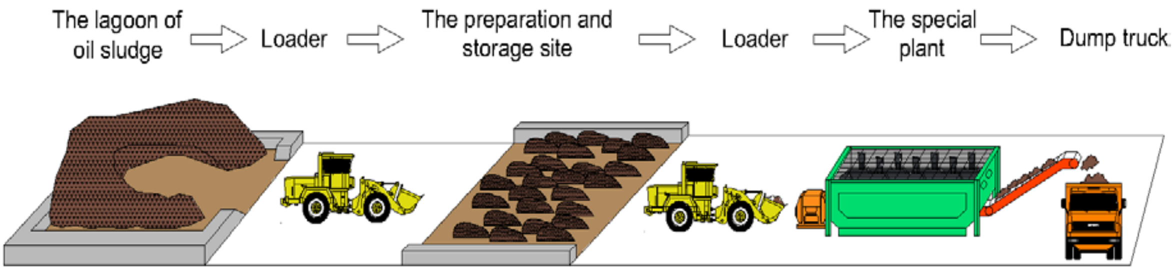

Figure 6. Operation schedule for oil sludge preparation using the plant.

Table 5. Physical and chemical parameters of the product "Prepared Solid Oil Sludge" (PSOS) – Akmal".

№	Parameter name	Parameter value
1	Grain (granulometric) composition up to 20 mm,% by weight, not less	95
2	Density, g/cm^3	1.4–1.7
3	Mass percentage of oil (oil products),% in the limit	10–30
4	Mass percentage of mechanical impurities,% in the limit	50–70
5	Mass percentage of water,%, not exceeding	20
6	Total specific effective activity of natural radionuclides, Bq/kg, not exceeding	1500

When developing the road building technology using oil sludge, the following factors were taken into account: characteristics and suitability of local mineral materials; the need and relevance of improving the mineral material granulometric composition; composition and readiness degree of oil sludge; methods of preparing the mixture; type of pavement and requirements for the structural layer made from the material including oil sludge; ensuring the specified productivity of the construction work flow; weather and climatic conditions of the construction area; type of binding material, its composition and features, and, if necessary, the composition and properties of active additives and activators. The road construction technology using oil sludge is carried out with the complex mechanization of the entire given process of work using modern high-performance machines and equipment. Physical and mechanical properties of the processed material in the structural layer of the pavement depend on compliance with the requirements for the properties of the source materials and on the total effect of sequentially performed process operations. Taking into account the factors mentioned above and specific features of the road construction technology development using solid oil sludge, the following methods of work performance are developed:

- the work performance technology with the preparation of an organo-mineral mixture based on oil sludge in a mixing plant and subsequent mixture transportation to the laying area;

- the work performance technology with the preparation of an organo-mineral mixture based on oil sludge by the "mixing on the road" method using mixing equipment (recyclers, mounted road milling machines).

The experimental and industrial implementation of research results was carried out by arranging 4 experimental road sections, the execution of works was conducted using the method called "mixing on the road" which was fulfilled by the recycler Wirtgen WR 2400 from 2016 to 2019. When determining the operational method, the key factor was the availability of mixing equipment (Wirtgen WR2400 recycler) and the possibility of its delivery to the sites, taking into account the optimal distance of oil sludge transportation of about 100 km. Pavement and base regeneration using recyclers is a popular and demanded method in our region, therefore, the recyclers are operated for the entire construction season on federal, regional and local roads, and the recycler drivers are experienced and highly qualified specialists, which is also considered significant for experimental construction. In 2019, the experimental road section was arranged during the repair of the Aznakayevo – VerkhniyeStyarle – Kuk-Tyaka highway km28 + 800 - km32 + 400 in the Aznakayevsky municipal region of the Republic of Tatarstan in accordance with the following designed structure (Figure 7).

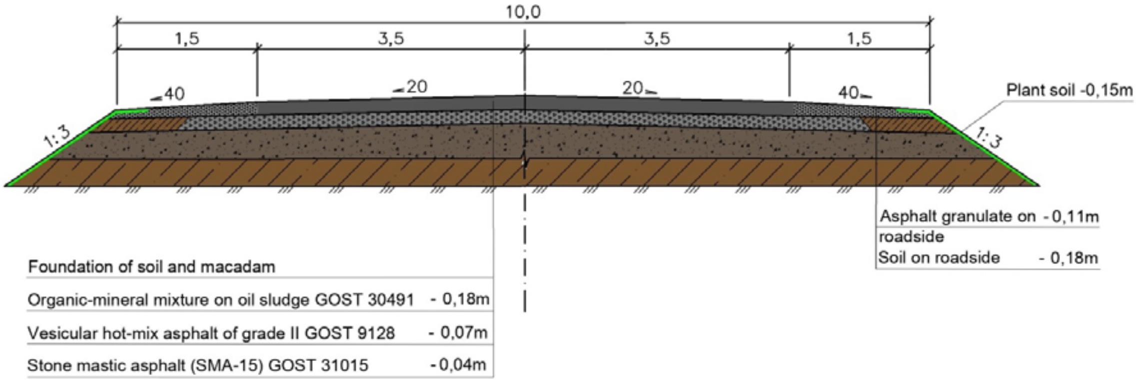

Figure 7. The design of pavement with the base of organo-mineral mixture based on oil sludge.

Firstly, the existing asphalt concrete pavement with the thickness of 5 cm was milled with a road milling machine and asphalt breakage was removed by dump trucks. Next, the base and the pavement were constructed and finishing works were carried out.

Manufacturing process of the pavement base made from organo-mineral mixtures based upon oil sludge is as follows:

The process of crushed stone and oil sludge delivery in the stacks was carried out by dump trucks.

Crushed stone spreading was fulfilled by the loader, planning was carried out by a motor grader.

Oil sludge spreading was fulfilled by the loader, planning was carried out by a motor grader.

Crushed stone and oil sludge mixing is carried out by Wirtgen WR2400 recycler (Figure 8).

Water was delivered and poured by a water-jetting machine.

The binder (Portland cement) was delivered by a cement lorry.

The binder (Portland cement) was spread by a cement spreader – semi-trailer van. (Figures 9).

Final mixing of materials was carried out by a recycler Wirtgen WR 2400.

The mixture was compacted using combination rollers with 8 passes along one track with overlapping the track 1/3 of the width of the drum with the speed of 1.5–2 km/h.

Mixture leveling and surface planning was performed by a grader. We also made control measurements of evenness, slopes and elevations.

Maintenance of the laid coat was carried out by pouring bitumen BND 90/130 with a flow rate of 0.8 l/m^2 taking into account pavement base tack coat which is applied before placing asphalt concrete mixture because asphalt concrete was applied first two days after pavement base construction according to the conventional process.

Figure 8. Recycler Wirtgen WR 2400.

Figure 9. Cement spreader – semi-trailer van Bomag BS12000.

The operation and monitoring of the experimental sections of the road under construction is carried out with the subsequent study of the samples of the material cutting out in accordance with regulatory requirements. We received the results of physical and mechanical parameters of the material and the total specific effective activity of radionuclides, all parameters meet to the requirements of the standard.

When comparing pavement estimated cost we considered the traditional pavement base made from imported crushed stone M800 and the base from an organo-mineral mixture based on oil sludge. We found out that it is possible to save 1,668,805 rubles, i.e. 30% of pavement base estimated cost due to the use of the developed material per 1 km (Fig. 10).

Thus, unlike other methods of oil sludge recycling such as pyrolysis, coking, microwave processing, burning, decanting, etc., [11–16] the proposed modern technology for pavement base construction allows making the oil sludge recycling cycle totally complete and to exclude the formation of industrial by-products, which contributes to the improvement of the environment ecological state in the areas of oil production and refining.

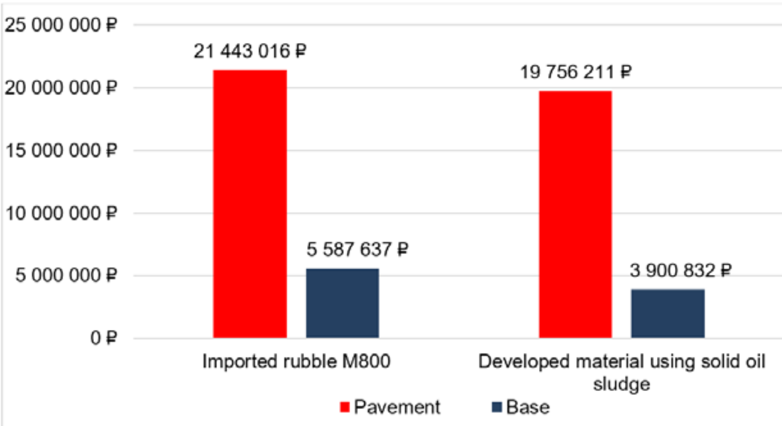

Figure 10. Pavement cost comparison using imported crushed stone M800 and organo-mineral mixture based on oil sludge.

4. Conclusion

1. Using experimental research we found the optimal composition of organo-mineral mixture based on oil sludge. Optimal content of oil sludge in composition of materials under development is 30 %, content of crashed stone M400 is 70 % and content of Portland cement is 6 % of organo-mineral mixture’s mineral part. The studied parameters of strength, water resistance coefficient, water saturation and swelling of the organo-mineral mixture based on oil sludge comply with regulatory requirements.

2. During experimental and industrial implementation of the research results we developed the pavement base construction technology using organo-mineral mixture based on oil sludge for four experimental road sections. It is carried out by commercially available road-building machines with a driving mechanism - a recycler using the “mixing on the road” method. We also fulfilled operation and monitoring of experimental road construction sections.

3. We developed an operation schedule for oil sludge preliminary preparation on the special plant to ensure its uniformity in composition and properties, which allows integrated use of oil sludge as a secondary raw material for road construction in modern conditions and is an integral part of rational use of natural resources and saving material resources.

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Contacts:

Olga Ilina, +7(987)2975616; ilinaon@inbox.ru

Ignat Ilin, +7(919)6379750; ilinignat97@mail.ru

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Дорожные органоминеральные смеси на основе нефтяного шлама

О.Н. Ильина *, И.Б. Ильин,
Казанский государственный архитектурно-строительный университет, г. Казань, Россия,
** E–mail: ilinaon@inbox.ru*

Ключевые слова: нефтяной шлам, органо-минеральные смеси, автомобильные дороги, технология строительства, утилизация

Аннотация. В настоящее время актуальное значение в дорожном строительстве приобретает разработка и внедрение современных технологий строительства с применением нефтяных отходов. Большая часть таких отходов хранится в прудах-накопителях, которые занимают огромные территории, загрязняют атмосферу, грунтовые воды, почву и наносят вред окружающей среде. Цель исследований является разработка составов органоминеральных смесей на основе нефтяного шлама и технологии строительства оснований автомобильных дорог с их применением. Методика экспериментальных исследований заключалась в определении показателей прочности, водостойкости, водонасыщения, набухания материалов различного состава, также устанавливались оптимальные пределы варьирования факторов, обеспечивающие требуемую надежность результатов. В результате исследований установлено, что оптимальное содержание нефтяного шлама в составе разработанных смесей составляет 30%, щебня – 70%, содержание портландцемента составляет 6%, физико-механические показатели органоминеральной смеси на основе нефтяного шлама соответствуют нормативным требованиям. При опытно-промышленном внедрении результатов исследований на 4 экспериментальных участках автомобильных дорог разработана технология строительства оснований автомобильных дорог из органоминеральной смеси на основе нефтяного шлама серийно выпускаемыми дорожно-строительными машинами с ведущим механизмом – ресайклером методом «смешения на дороге». Разработана технологическая схема предварительной подготовки нефтяного шлама на установке. Подготовленный нефтяной шлам представляет собой однородное по цвету, зерновому составу, массовой доли воды и нефти вторичное сырье для дорожно-строительных материалов. Предложенная современная технология строительства оснований автомобильных дорог позволяет сделать цикл утилизации нефтяных шламов полностью завершенным и исключить образование побочных отходов. Это является неотъемлемой частью рационального природопользования и экономии материальных ресурсов, способствует улучшению экологического состояния окружающей природной среды в районах добычи и переработки нефти.

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Контактные данные:

Ольга Николаевна Ильина, +7(987)2975616; ilinaon@inbox.ru

Игнат Борисович Ильин, +7(919)6379750; ilinignat97@mail.ru